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THE DETERMINATION OF THE STABILITY OF STRUCTURES OF COMPOSITE MATERIALS SUBJECTED TO INTENSE SURFACE HEATING

(K OPREDELENIYU NESUSHCHEI SPOSOBNOSTI KONSTRUKTSII IZ KOMPOZITSIONNYKH MATERIALOV PRI INTENSIVNOM POVERKHNOSTNOM NAGREVE)

by

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V. A. Kireev

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AUTHORS' SUMMARY

The effect of destructive heating applied to the surface of a cylindrical shell of composite material subjected to compressive end loads or uniform external pressure is considered theoretically, and the results compared with those of previously reported experiments by the same authors.

The reduction in the value of critical load which occurs with increasing exposure time is considered in terms of the reducing structurally effective thickness of the wall.

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In a previous article[1], a method was proposed for the calculation of the critical load upon longitudinal compression of orthotropic shells subjected to non-uniform heating over their thickness; the method is based on the Kirchhoff - Love hypotheses. A comparison of theoretical and experimental values of critical loads shows that, in cases where there is intense, high-temperature heating of the shell, the increase in the theoretical value above the experimental one can reach 50%. This is explained by a non-uniformity through the thickness of the material of the polymer matrix in the associated physico-mechanical characteristics. For high applied temperatures, several zones are formed in the walls of material - coked, pyrolysed and unaffected. The instantaneous value of the supporting ability of the shell is determined by the thicknesses of these zones, their rigidity and stability characteristics, this ability being affected by the thermal stress produced in the coked and pyrolysed zones and by the stresses created due to pressure arising from the gaseous products of pyrolysis which can lead to layer separation in the material; the layers, however, retain their individual rigidity characteristics but the structure will not take an external load. External loads are accepted basically by unaffected or supporting zones of the wall, the thickness of which decreases with increase in temperature.

Below, a method is investigated for the calcualtion of orthotropic laminae and shells with a supporting zone, the thickness of which varies with time. The basic difference between this method and that proposed above lies in the calculation of the change in the thickness of the supporting layer when determining the rigidity characteristics of the structure.

In the estimation of the critical loads and parameters of the wave formation of smooth cylindrical, orthotropic shells, heated unevenly over their thicknesses, we may start with the characteristic equation:

$$-N_x\lambda_1^2 - N_y\lambda_2^2 + 2N_{xy}\lambda_1\lambda_2 = D_{11}\lambda_1^4 + 2(2D_{33} + \nu_2 D_{11})\lambda_1^2\lambda_1 + D_{22}\lambda_2^4 + \frac{E_2 h}{R^2}\,\frac{\lambda_1^4}{\lambda_1^4 + (E_2/G - 2\nu_2)\lambda_1^2\lambda_2^2 + (E_2/E_1)\lambda_2^4}$$

where $\lambda_1 = m\pi/\ell$; $\lambda_2 = n/R$; m = half wave value in the longitudinal direction; ℓ = length of the shell; R = radius of the middle surface of the shell; N_x^o, N_y^o, N_{xy}^o are subcritical forces; x, y are coordinates on the middle surface area; E_1, E_2, G, D_{11}, D_{22}, D_{33}, are stiffness parameters; ν_1, ν_2 are Poisson coefficients. For longitudinal compression of the shell, $N_x^o = - \sigma h$;

$N_y^o = N_{xy}^o = 0$; for the action of an even, external pressure, $N_y^o = -qR$; $N_x^o = N_{xy}^o = 0$, where σ is the axial stress and q is the pressure intensity.

The temperature distribution in the case of high-temperature heating of the structure on one side over the wall thickness at a moment in time τ , we shall, taking the one-dimensional problem, denote by $T(z_1\tau)$, where z is the distance from the mean surface to any point of the wall along the external normal. The limit of the load bearing zone can be determined with the help of the critical temperature[2], T_{Kp} , the value of which depends on the stress-strain state involved, the shape and material of the structure; it is established experimentally. The thickness of the lead bearing zone $h(\tau)$ is represented by:

$$h(\tau) = \begin{cases} h_0 & \text{if } T_s \geqslant T_{Kp}; \\ h_0/2 + z_* & \text{if } T_s > T_{Kp};\ T(z_1\tau) < T_{Kp}; \\ 0 & \text{if } T(z_1\tau) \geqslant T_{Kp}, \end{cases}$$

where z_* is the root of the equation:

$$T_{Kp} = T(z_*;\tau); \qquad (1)$$

h_0 is the initial thickness of the wall; T_s is the temperature of the surface being heated.

Let the moduli of elasticity of the material of the wall E_1^* , G^* depend on the temperature $T(z)$, the Poisson coefficients ν_1, ν_2 be independent of it, and the moduli E_1 , E_2 be connected by the relationship; $E_2\nu_1 = E_1^*\nu_2$. Then the rigidity of the load bearing zone of an element of a thick-walled structure will be defined by the formulae:

for tension-compression:

$$E_a h = \int_{-05h(\tau)}^{0.5h(\tau)} E_a^*[T(z)]dz \qquad (a = 1,2); \qquad (2)$$

for shear:

$$Gh = \int_{-0.5h(\tau)}^{0.5h(\tau)} G^*[T(z)]dz; \qquad (3)$$

for bending:

$$D_{aa} = \overline{} \int_{-0.5h(\tau)}^{0.5h(\tau)} E_a^* \left[T(z)\right](z - z_0)^2 dz: \tag{4}$$

for torsion:

$$D_{33} = \int_{-0.5h(\tau)}^{0.5h(\tau)} G^* \left[T(z)\right](z - z_0)^2 dz; \tag{5}$$

where:

$$z_0 = \frac{\int_{-0.5h(\tau)}^{0.5h(\tau)} E_1^* \left[T(z)\right] z dz}{E_1 h} \quad . \tag{6}$$

In order to calculate the stiffness characteristics, the critical loads and the wave-formation parameters, a programme in FORTRAN language was drawn up for the BESM-6 computer. The transcendental equation (1) was evaluated using the half division method, while the definite integrals in expressions (2) to (6) were calculated with the help of the Gauss eight-point equation.

By means of this programme, a calculation was carried out on a glass plastic layer on a phenol formaldehyde adhesive, the temperature of the external surface of which changes with time linearly, at a rate $b = 5^{\circ}/s$ for constant values of either longitudinal load or evenly-distributed external pressure.

In the determination of the thickness of the supporting layer, as the critical temperature a value of 503 K was chosen[2]. The physico-mechanical characteristics of the material and their dependence on temperature were taken from the previous report[1].

The change in the thickness of the supporting layer $h(\tau)$, the critical load under longitudinal compression $\sigma_{Kp}(\tau)$ and the external $q_{Kp}(\tau)$ of the coating with time is represented by broken curves in Figs 1 and 2. The solid curves correspond to a calculation using a constant thickness of supporting layer. It is seen that the thickness of the supporting layer is equal to the initial thickness of the wall if the time of heating does not exceed a value $\tau_{Kp} = (T_{Kp} - T_0)/b$, where T_0 is the initial temperature. As Fig 2a shows, the experimental data taken from Ref 1 agrees more satisfactorily with the curve obtained by taking into consideration the change in the thickness of the supporting layer. This indicates that the method of calculation proposed can be applied to the analysis of the rigidity of thick-walled structural units subjected to conditions of intense heating at high temperatures.

In order to evaluate the effect of lateral displacement on the critical stress of longitudinal compression, a calculation was carried out of a uniformly heated cylindrical shell of the same material. For this, the starting equation[3] was:

$$\sigma = \frac{h_0^3}{12\lambda_1^2\Delta}\left[\lambda_1^2 b_{11} + 2\lambda_1\lambda_2 b_{12} + \lambda_2^2 b_{22} + \frac{h_0^2}{10}(a_{44}\lambda_1^2 + a_{55}\lambda_2^2)(b_{11}b_{22} - b_{12}^2)\right] + \frac{h_0 B_{66}\omega_2}{R^2}\,\frac{\lambda_1^2}{b_{11}b_{22} - b_{12}^2}\ , \qquad (7)$$

where $\Delta = 1 + \frac{h_0^2}{10}(a_{55}b_{11} + a_{44}b_{22}) + a_{44}a_{55}\frac{h^*}{100}(b_{11}b_{22} - b_{12}^2)$;

$$b_{11} = \lambda_1^2 B_{11} + \lambda_2^2 B_{66}; \quad b_{22} = \lambda_2^2 B_{22} + \lambda_1^2 B_{66}; \quad b_{12} = \lambda_1\lambda_2(B_{12} - B_{66});$$

$$B_{11} = E_1^*/(1 - \nu_1\nu_2); \quad B_{22} = E_2^*/(1 - \nu_1\nu_2); \quad B_{66} = G_{12} = G^*;$$

$$B_{12} = \nu_2 B_{11}; \quad a_{44} = 1/G_{23}^*; \quad a_{55} = 1/G_{13}^*; \quad \omega_0 = B_{11}B_{22} - B_{12}^2\ .$$

It was assumed that $G_{13}^* = G_{23}^* = G^*$.

By way of the numerical minimisation of equation (7), it was found that, at temperatures close to the critical figure, the value of the critical compressive force was reduced by 1%. It is to be supposed that, in the case of a non-uniformly heated coating, the effect of lateral displacements will be even less pronounced. From this it can be seen that the role of lateral displacements in the determination of critical loads is less important than changes in thickness of the supporting layer.

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Figs 1&2

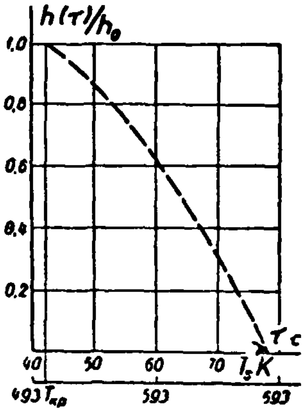

Fig 1 The change in thickness of the supporting layer of the coating

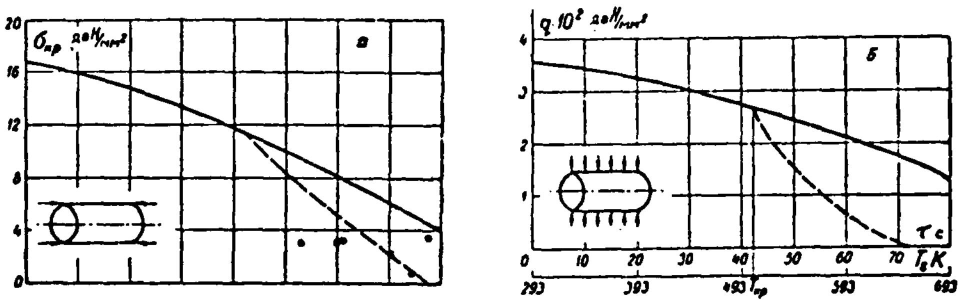

Fig 2 Critical load for shells

a) with longitudinal compression
b) with external pressure

Note: σ_{kr} ДаН/mm^2 = $\sigma_{critical}$, pressure N/mm^2

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